# Background Radiography for Border Inspections

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K. N. Borozdin *et al*., “Radiographic imaging with cosmic ray muons,” *Nature*, **422**, 277 (2003).

W. C. Priedhorsky, *et al*., “Detection of high-Z objects using multiple scattering of cosmic ray muons,” *Review of Scientific Instruments*, **74**, 4294 (2003).

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# Contraband Problem / Muon Solution

- Smugglers may try to bring across the border a variety of controlled materials (e.g. U and Pu).
- To get past radiation detectors, these items will need to be shielded, so there will also be lead or other high Z shielding material.
- A characteristic of high Z material is that charged particles will experience greater multiple scattering as they traverse them relative to lower Z material.
- So, our proposed method of detecting a *threat object* is to measure the multiple scattering of cosmic ray muons that pass through a cargo container or vehicle.
- Any successful threat object detection method must be automated, obtain an answer in near real time, be robust to all cargo scenarios, and have an acceptable reliability.

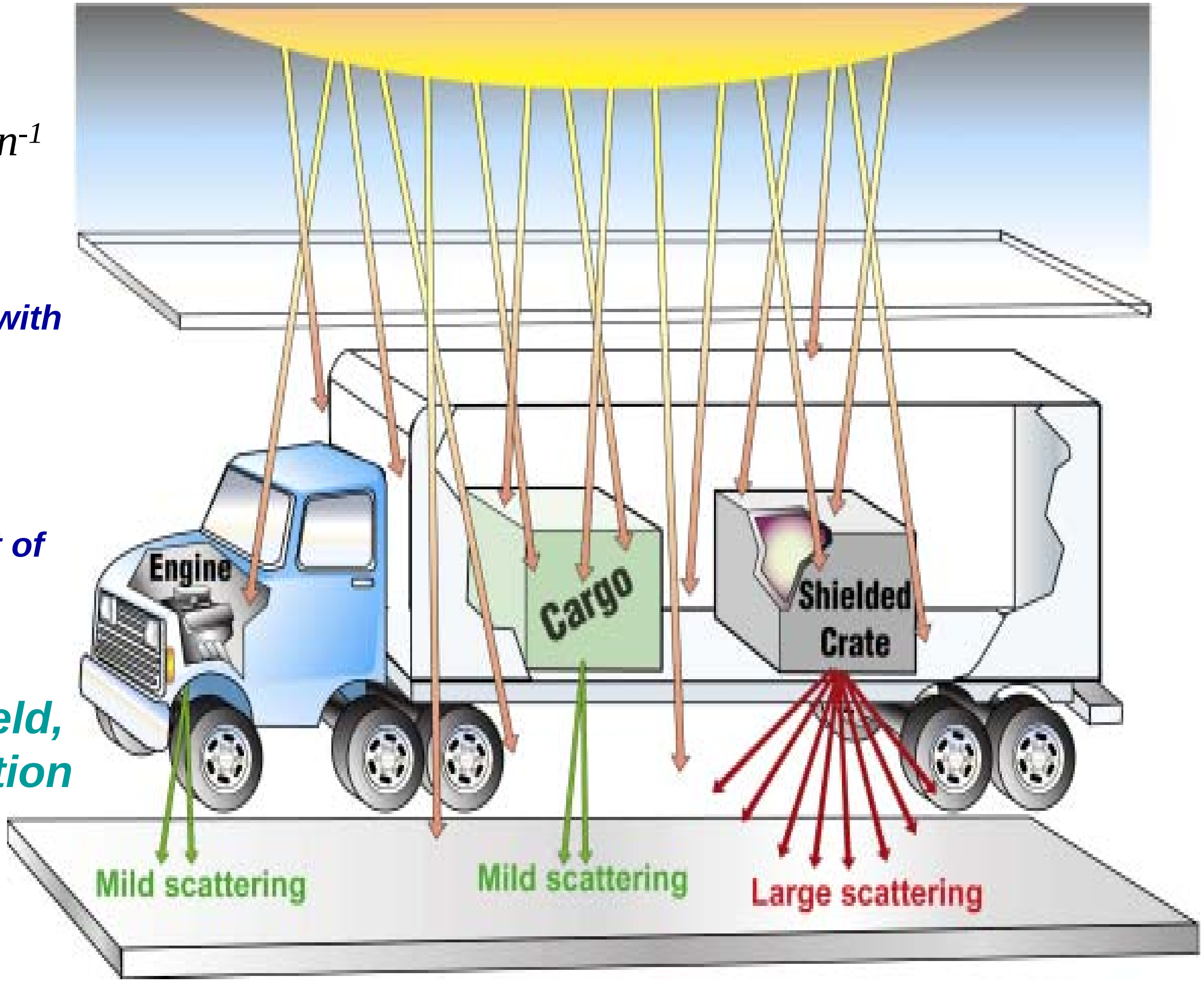
# Muon Radiography Operational Concept

*Muon flux ~ 1 $cm^{-2}min^{-1}$*

***Objective:***
***penetrating radiography with no artificial dose***

***Application:***
***Prevent illicit movement of nuclear materials***

***The heavier the shield, the easier the detection***

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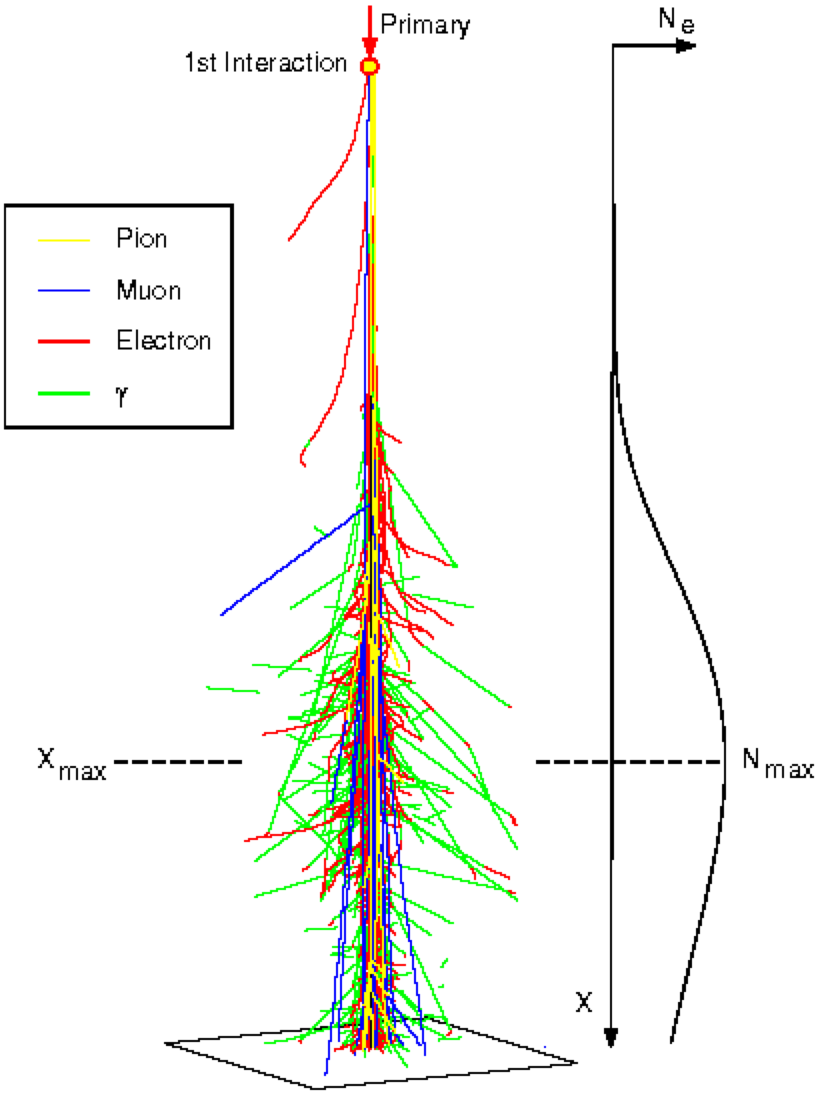
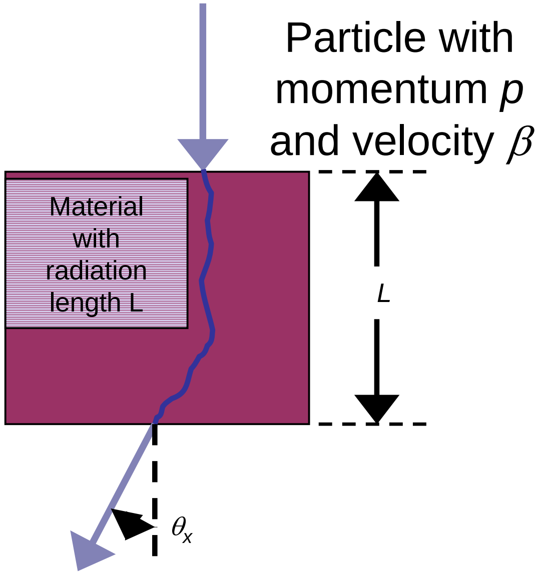
# Cosmic Ray Muons

- Primary cosmic rays strike the atmosphere and generate a cascade of secondary particles.
- Muons are the dominant particle at the Earth's surface.
- Most muons can penetrate tens of meters of rock or more.
- Muons arrive at a rate of 10,000 per square meter per minute (at sea level).
- The spectrum of cosmic ray muons (energy, arrival angle) is well documented. Peak at 3 GeV



# Physics of interaction: multiple scattering




Scattering distribution is approximately Gaussian

$$\frac{dN}{d\theta_x} = \frac{1}{\sqrt{2\pi}\theta_0} e^{-\frac{\theta_x^2}{2\theta_0^2}}$$

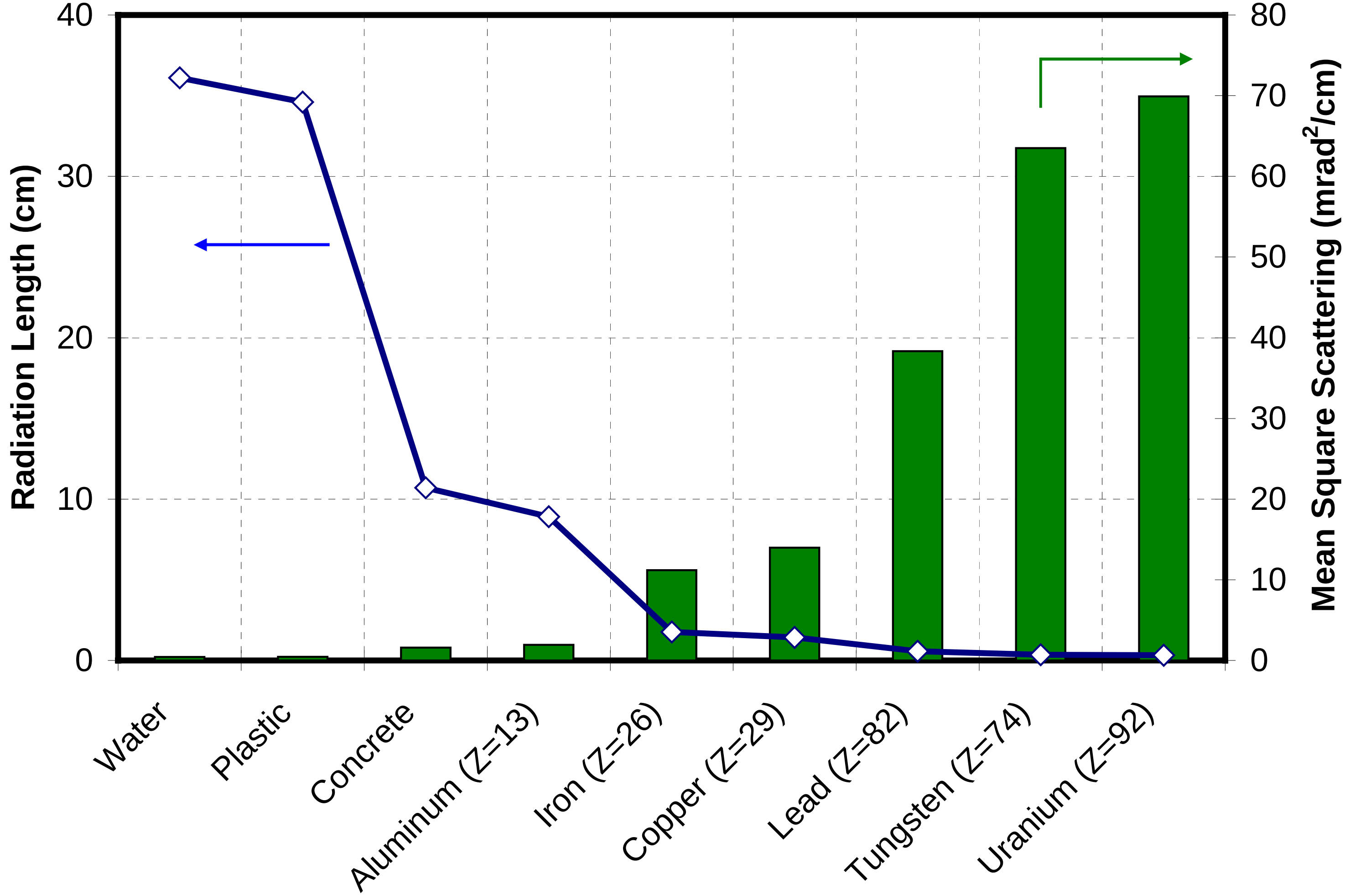
and the width of the distribution depends on material and muon properties ($\lambda$ is a radiation length)

$$\theta_0 = \frac{13.6}{p\beta}\sqrt{\frac{L}{\lambda}} + H.O.T.$$

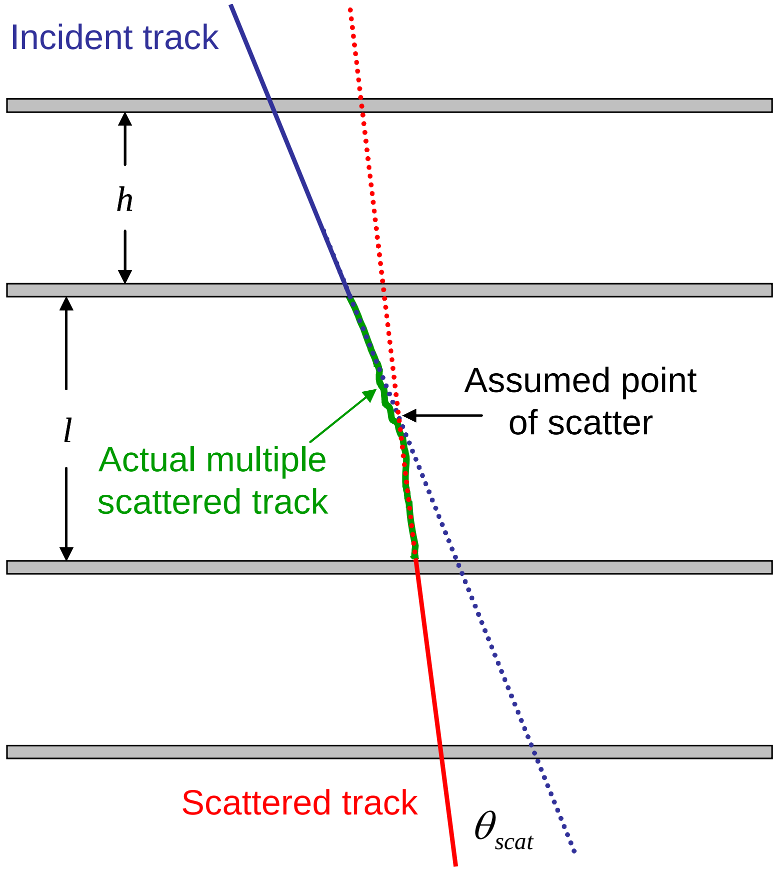
Scattered particles carry information from which material may be identified.

| Material | $\lambda$ , cm | $\theta_0$, mrad* |
|---|---|---|
| Water | 36 | 2.3 |
| Iron | 1.76 | 11.1 |
| Lead | 0.56 | 20.1 |
| *10 cm of material, 3 Gev muons | | |

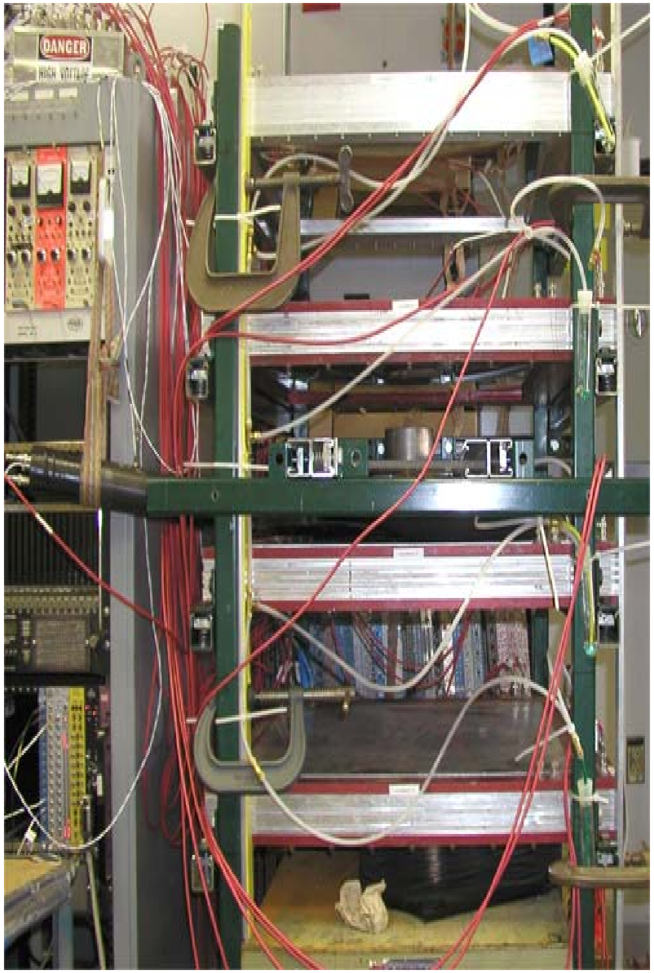
# Radiation Lengths and Mean Square Scattering for Example Materials



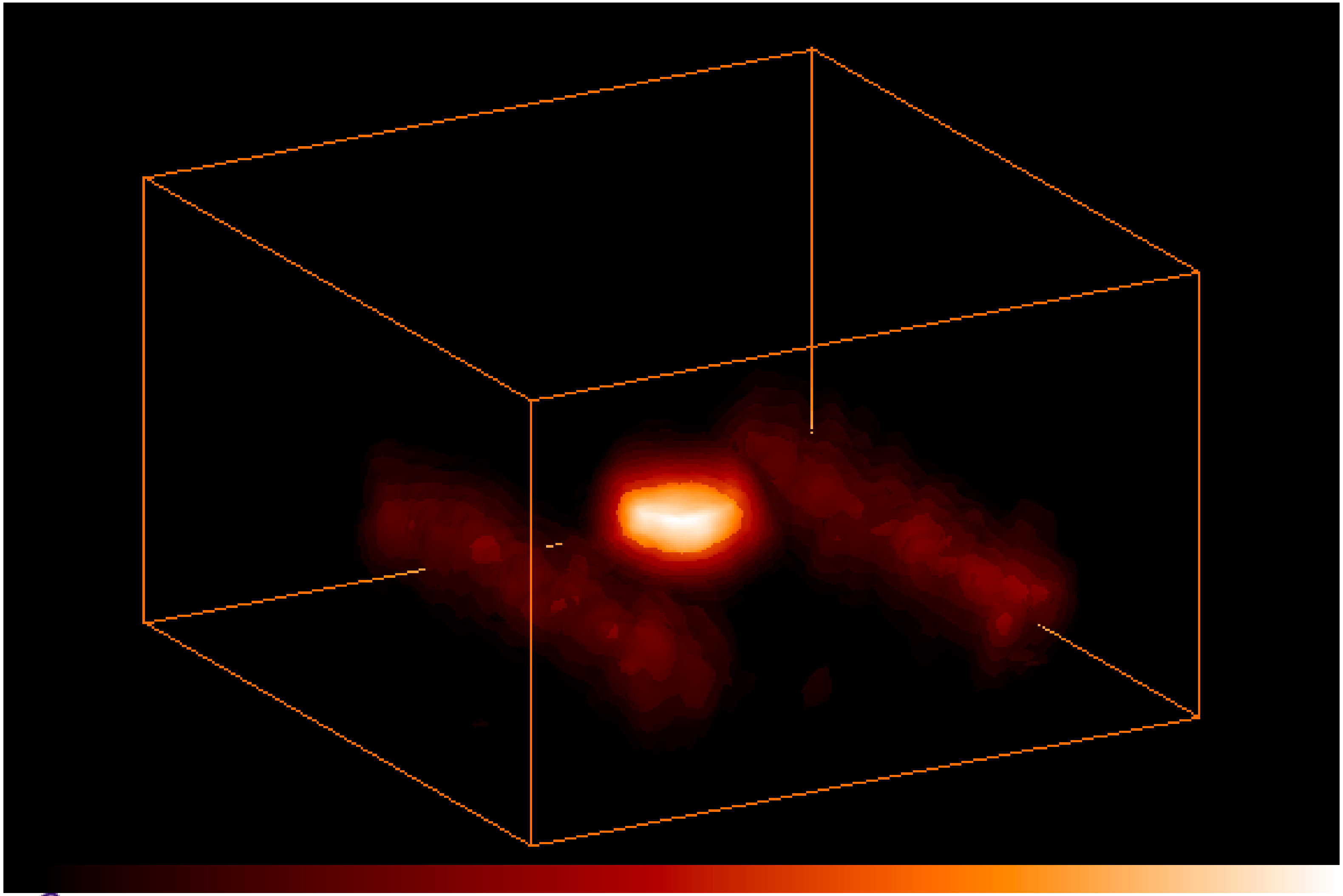
# Prototype Experiment



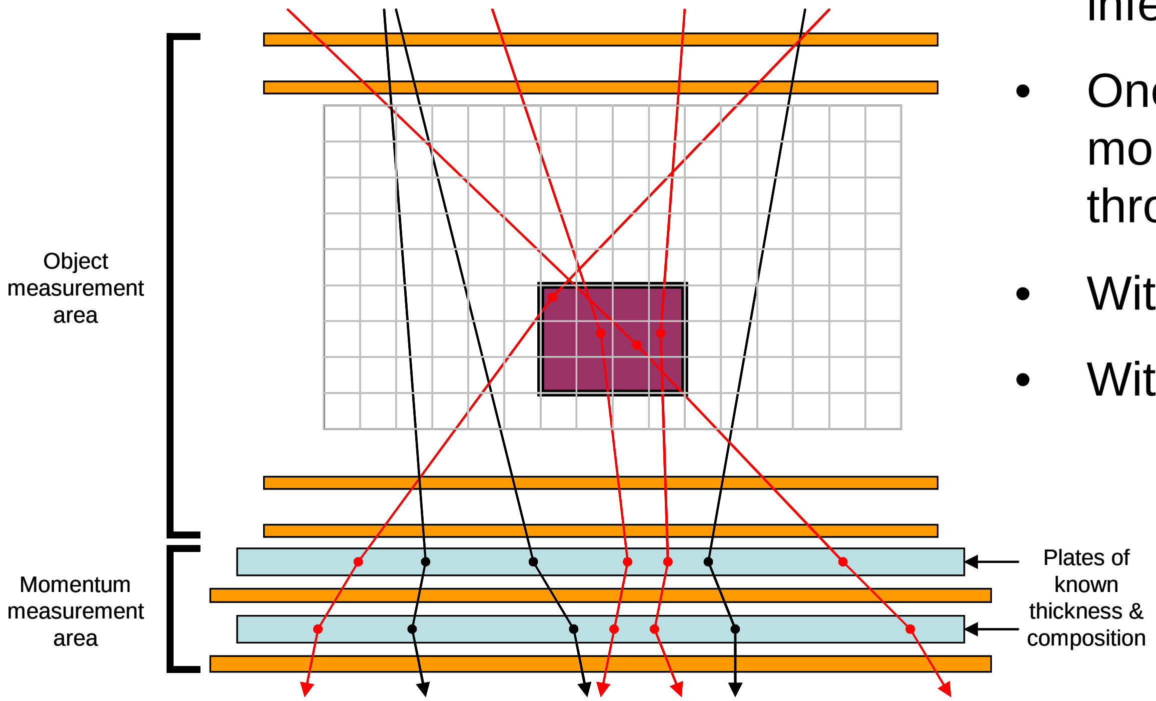

*The magnitude of scattering is exaggerated for illustrative purposes.*



# World’s First Cosmic Ray Muon Radiograph Using Trajectory Reconstruction



# Momentum Estimation




- Measuring particle momentum increases confidence in material inference.
- One method is to estimate momentum from scattering through known material.
- With 2 plates $\delta p/p$ is about 50%.
- With $N$ measurements:

$$\frac{\delta p}{p} \rightarrow \sqrt{\frac{1}{2N}}$$

# Border Inspection Concept

- First, is something producing large scattering?
  - Almost all cars, trucks and containers are harmless and should be quickly assessed as “uninteresting” and passed through.
- Second, is an interesting item an actual threat?
  - If you find that there is something generating a lot of scattering, is it a big piece of steel or a smaller piece of lead or SNM?
- Third, if a threat object is suspected, where is it and what does it look like?
  - To decide what you do next, you want to get more information on object size, shape, location, etc.

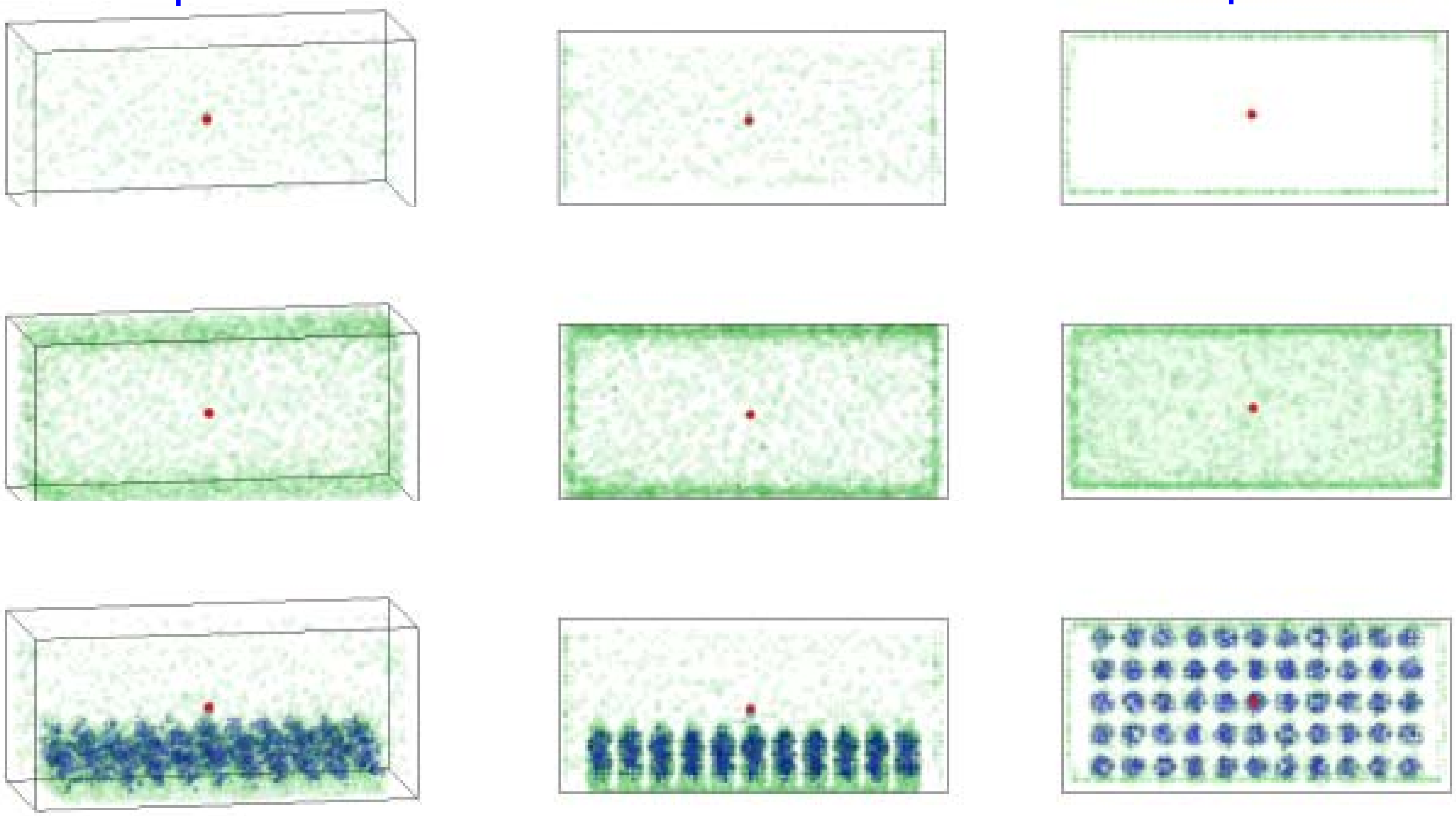
# Maximum Likelihood Tomographic Reconstruction
# 28x28x64 voxellation, 1 minute of data

**3D Perspective View** | **Side View** | **Top View**

**U in empty container**

**U in distributed Fe**

**U and car differentials**



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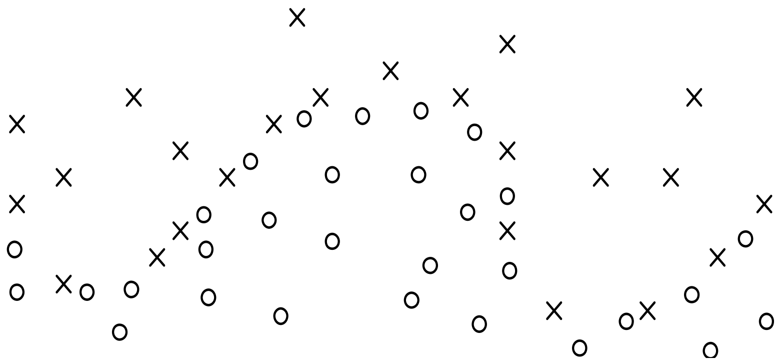
# Classification

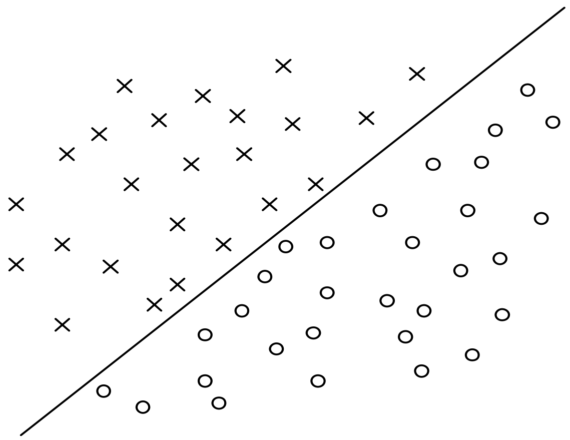
- Instead of using the data to create an image to find an object, we sought to determine directly from the data whether a threat object is present.

- We asked the LANL machine-learning folks about classifiers; they suggested using a support-vector machine (SVM).

# Support-Vector Machines



Thousands of points in 27-dimensional space



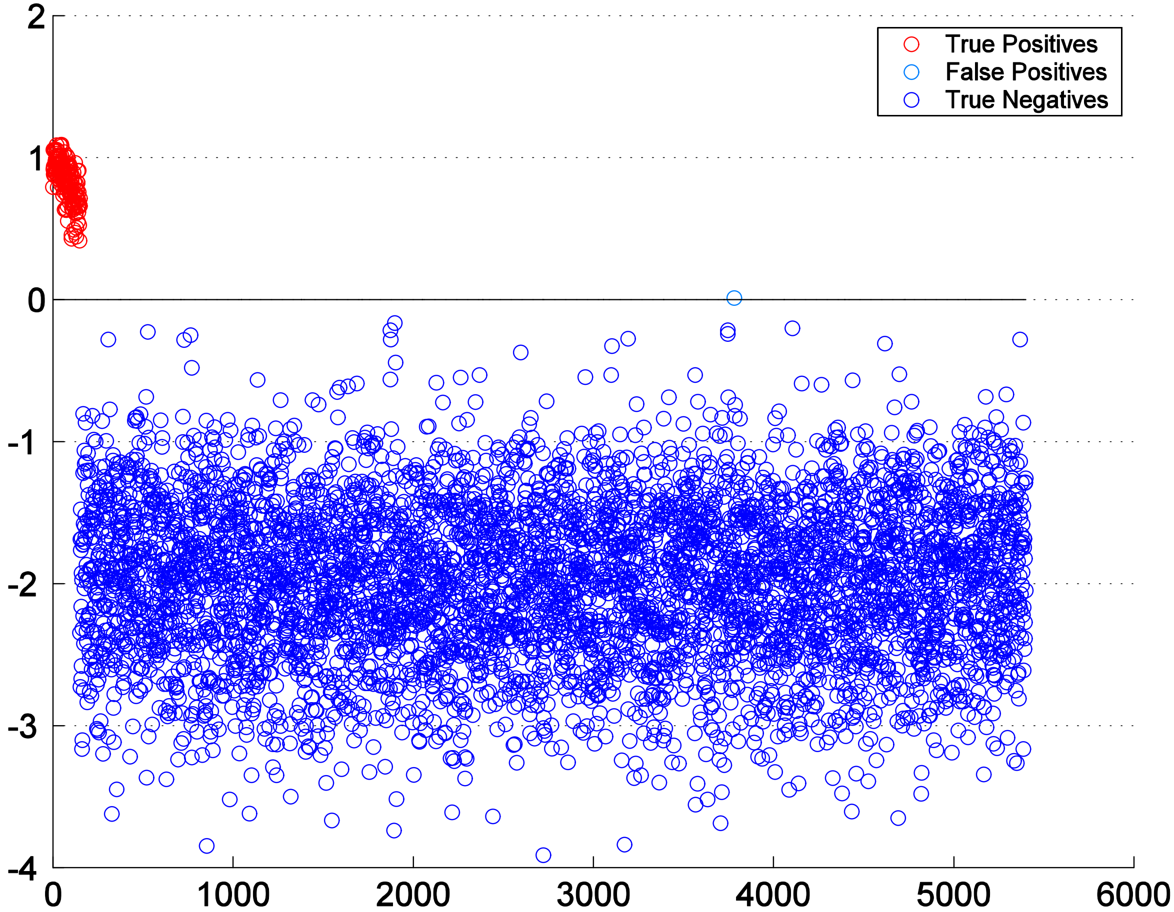
Thousands of points in infinite-dimensional space

- Linear classification is made possible by nonlinearly embedding the data into an infinite-dimensional function space.
- Given a kernel $k(x, y)$, the embedding maps $y$ to $x \mapsto k(x, y)$.
- For $k(x, y) = e^{-\Gamma \|x-y\|^2}$, the data is mapped to a simplex; any two subsets can be separated by a hyperplane.

# SVM Implementation

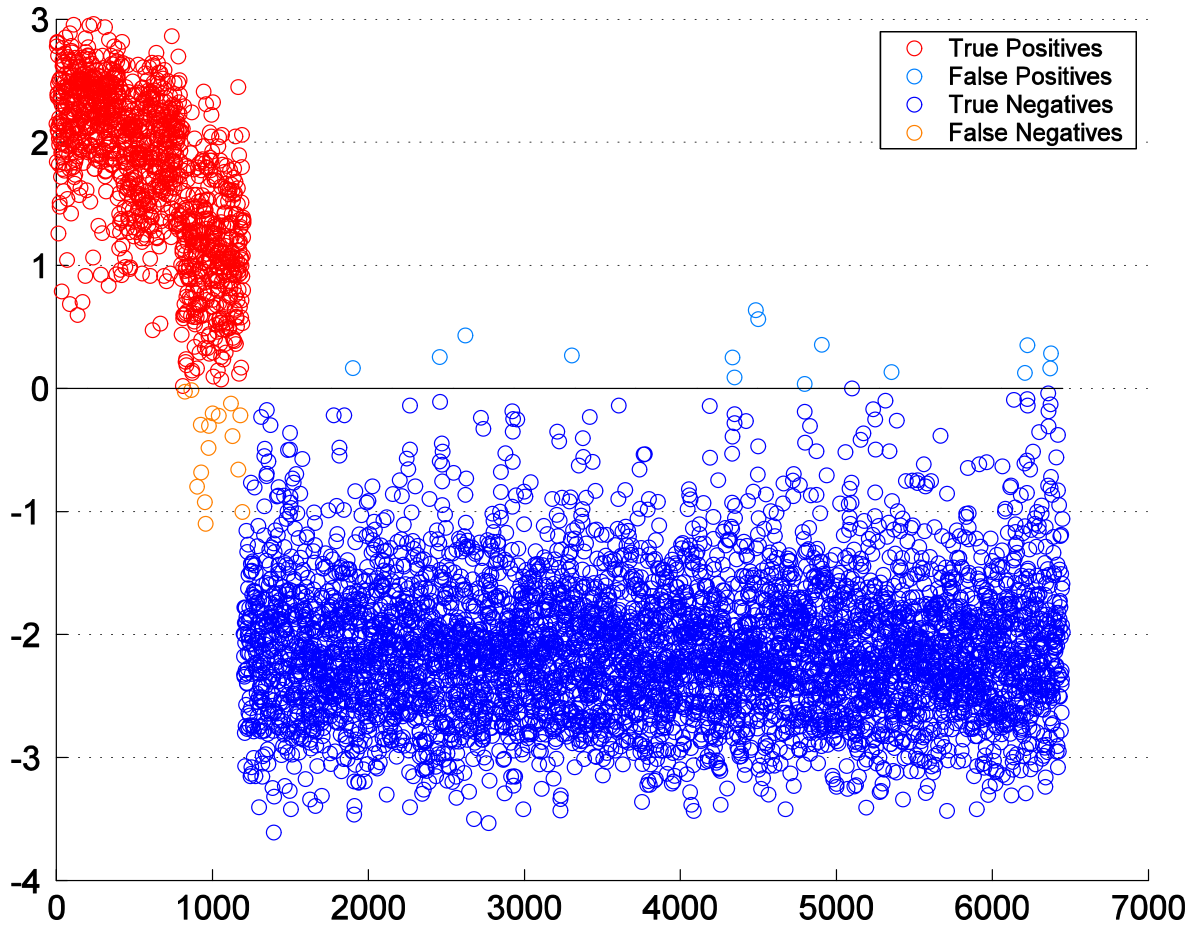
- The classifier is trained using muon-scattering data generated by computer simulations of cargo containers containing a variety of materials, some with a threat object and some without.
- The features for each sample are the mean squared scattering (angle times energy) for each 10-cm voxel in a 3-voxel cube surrounding the sample location.
- A muon's scattering is assigned to each voxel that the muon is estimated to have passed through (using incident track up to the assumed point of scatter, then the scattered track).
  - Alternatives: assign scattering just to the PoCA voxel; or weighted by inverse-distance from the PoCA.

# Results---Test Data




Positive samples have 20-kg U sphere centered on the central voxel.

# Results---Offset Test Data




Positive samples have 20-kg U sphere centered on a vertex of the central voxel.

# Clustering for Locating Objects

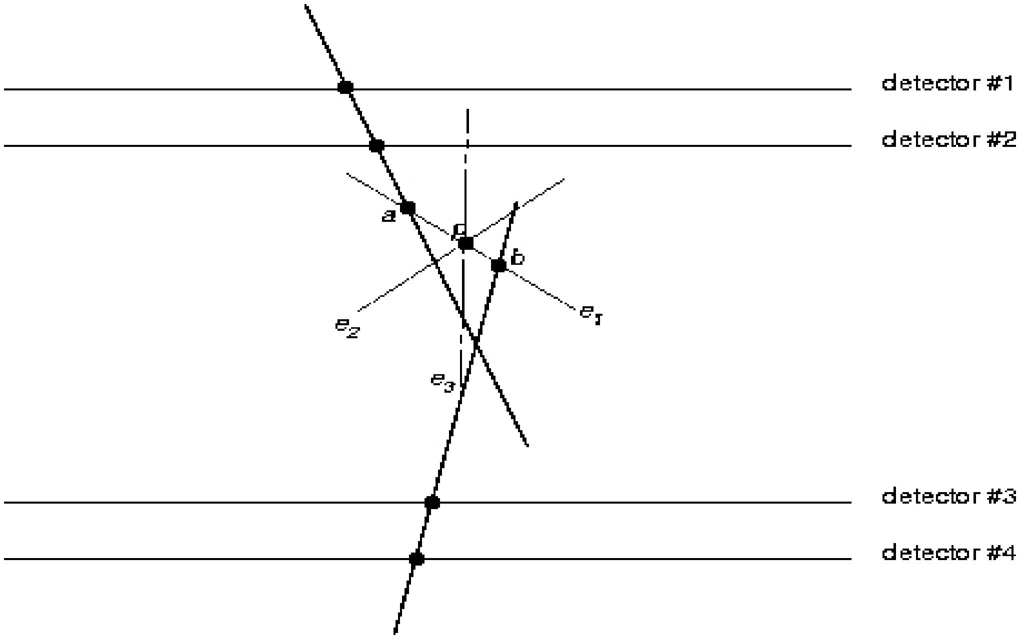
- The SVM works well for 3-voxel cubes; what about a whole container?
- Testing too many locations will allow test errors to accumulate.
- We identify a small number of locations to test by using a clustering routine.
- The cluster centroids are considered the candidate locations for a threat object, and passed to the classifier.

# Clustering algorithm

- A selection of the most significantly scattered muons is used for the clustering algorithm.
  - Scattering significance is the product of scattering angle and estimated muon energy.
  - The number of muons selected, ~ 100, can vary with the cargo weight, the duration of muon exposure, and the minimum size of threat object to be detected.
- A *k*-means clustering algorithm is used to find the clusters.
  - The largest cluster is iteratively checked for possible division, according to a criterion of the form $r_{p+} + r_{p-} < \gamma r_p$.
  - Stopping criteria involve the size of $\gamma$, the number of clusters, and the size of the smallest cluster.
- The cluster centroids are determined and passed to a classifier.
  - The centroid of each cluster is the point having the least total distance to each point of the cluster, as measured by a physics-based distance function.

# The Distance Function

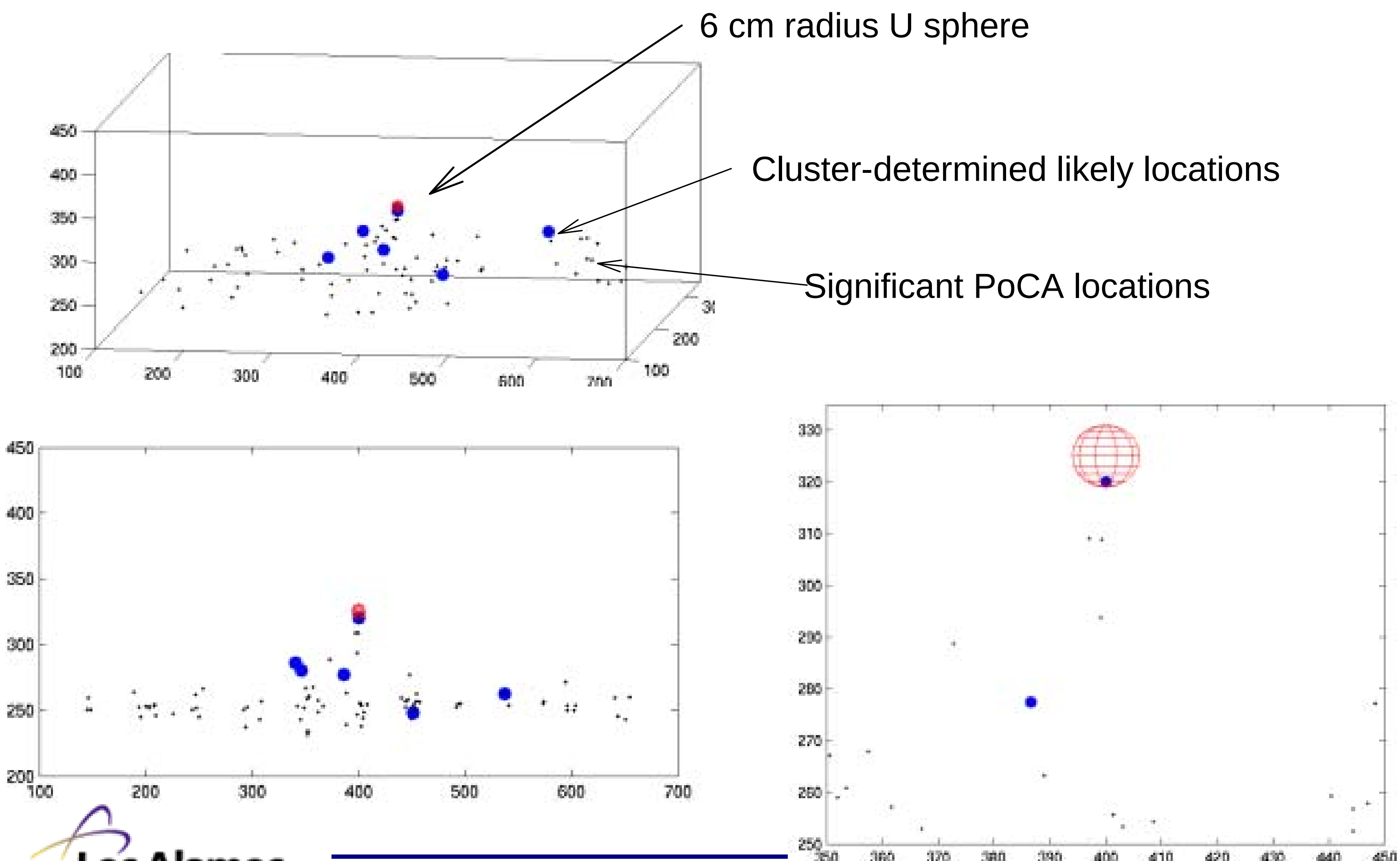
- Uses the single-scatter approximation to associate a point with each muon.
- Choice of weights incorporates the uncertainty of this approximation.
- Orthonormal coordinate vectors for each muon:
  - $e_1$: orthogonal to both paths
  - $e_2$: in direction of the deflection
  - $e_3$: follows tracks most closely




$$d_j(s) = \sqrt{\sum_{i=1}^{3} \left(\alpha_{ji}(s - p_j) \cdot e_{ji}\right)^2},$$

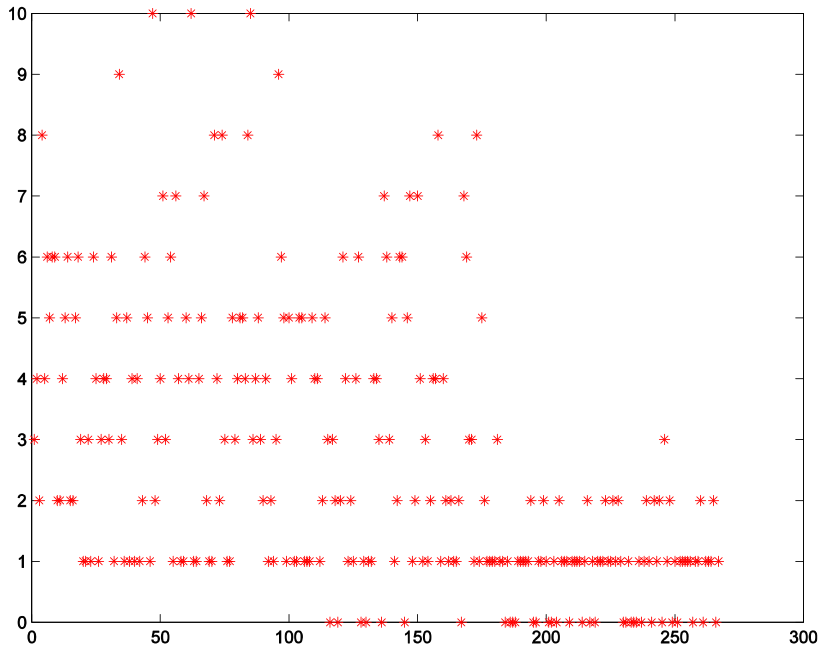
$$d_{jk} = d_j(p_k) + d_k(p_j).$$

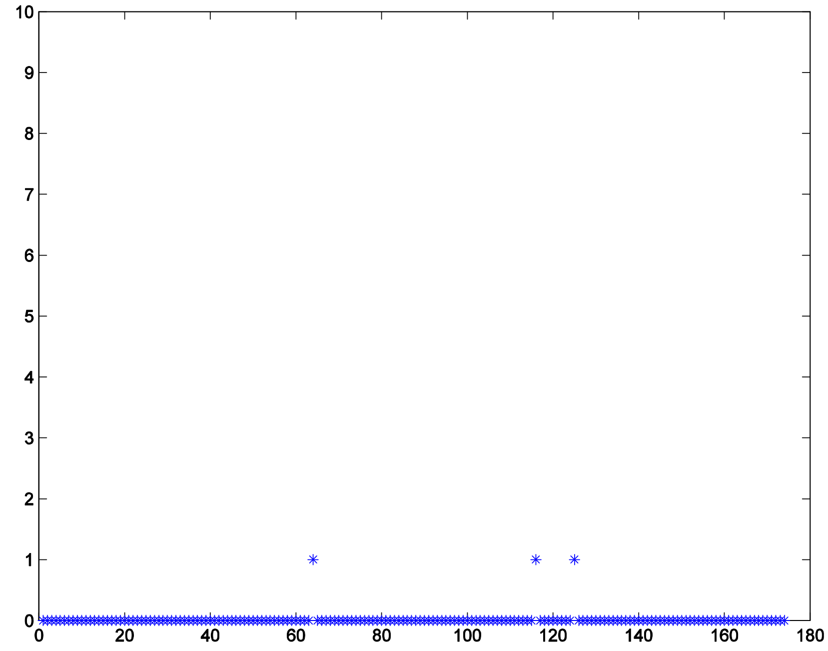
# Clustering Results for Case 1c-105
# (Uranium Sphere with Significant Iron Background)



# Preliminary Results---Classifying Cluster Locations

Number of positively-classified samples per truck




87% of trucks with a threat object have at least one positive sample (100% for common cargo scenario)

99% of trucks with no threat object have no positive sample